Beam Dynamics Studies in Support of a Flat-Beam Injector

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Femtosource Internal Review

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Our Charge:

Investigate the limitations of the flat-beam source:

Develop PARMELA and/or other models of the A0 experimental facility. Calibrate the model with experimental results from A0. Use the model to investigate the limits of charge, emittance, emittance ratio, energy spread and bunchlength for a flat-beam electron source. Integrate work with experimental results to develop the aims of the program.

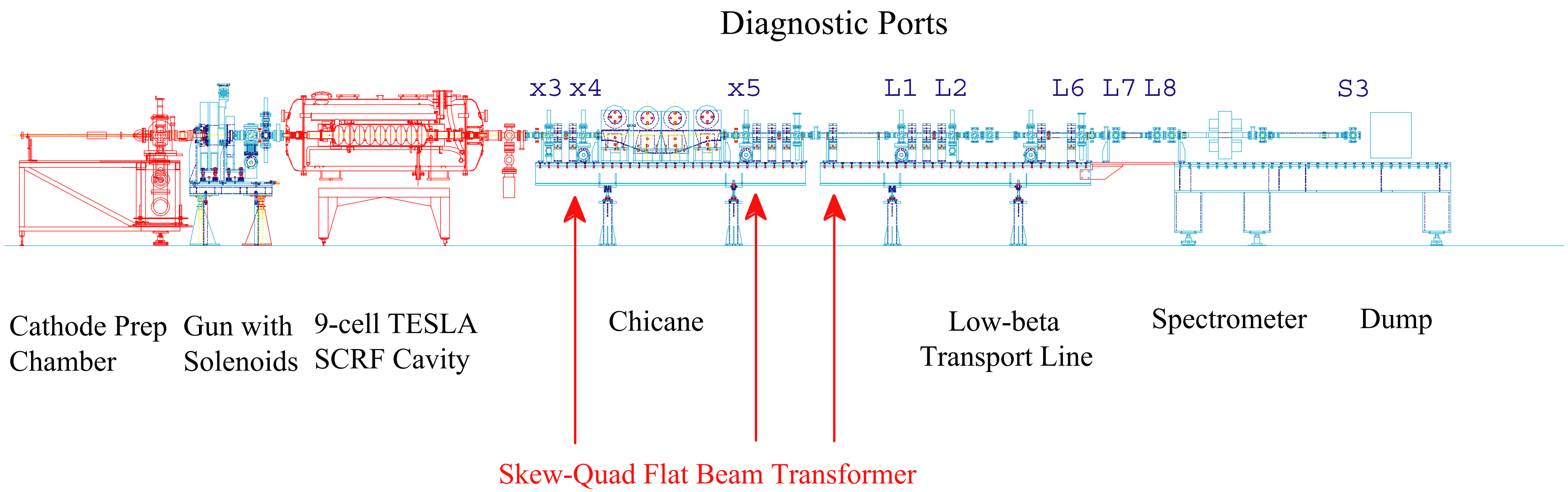
Perform experiments at the A0 facility:

Gain experience with operations at A0. Develop understanding of diagnostics, instrumentation, control systems, data acquisition, limitations of the facility. Develop facility improvements aimed at better understanding of flat-beam production. Experimentally determine the effects of variation in charge, RF gun phase and amplitude, solenoid field, quadrupole channel, bunchlength, etc for a flat-beam electron source? What are the limits on emittance ratio for a flat beam from the injector? What are the phenomena limiting performance in such sources? Investigate other possible means of producing flat beams: Is a non-linear channel advantageous?

A group effort

S. Lidia	Experiments at A0. Coordination of theory and simulation effort in support of experiments.
B. Rimmer	MAFIA RF gun modeling and design. Beam dynamics in the RF gun. High power operation of RF gun.
S. Wang	PARMELA modeling and beamline design. Beam dynamics from the gun through the round-to-flat transformation.

A0 Photoinjector



A0 Photoinjector Parameters

Normal Operation (round beam)

Gun Gradient	35-40 MV/m on cathode
9Cell SC cavity	12 MV/m E_{acc}
Pulse structure	1 μsec bunch spacing
# bunches	10-600 (10-20 typical)
RF 1.3 GHz	30-600 μsec @ 1Hz
Cathode	Cs2Te Typ Eff ~ 1-2%
Laser UV Energy	1-5 μJ/ bunch
Q(nC)=2.125Eff(%)U(μJ)	1-10 nC/ bunch
Total Energy after gun	4.5-5 MeV
Total Energy after 9cell	17-18 MeV
Compressor dl/(dp/p)	84mm
Gun solenoids	1200 Gauss peak typ
Inj RF Phase from 0 xing	40-50 deg
Laser spot on cathode σ	0.7-1.6mm

A0 PhotoInjector Parameters(2)

Uncompressed

Emittance $\gamma\varepsilon$ rms normalized	3.7e-6m @1nC
	12.6e-6 @8nC
Momentum spread σ_p/p	0.25-0.38%
Bunch length σ	1.6mm @1nC
	2.9mm @8nC
Peak Current	75-330A

Compressed

Bunch length σ	0.55mm
Peak Current	218-1740A

Femtosource Injector Parameters

Beam parameters:

Energy	10 MeV
Charge	1 nC
Normalized rms horizontal emittance	20 mm- mrad
Normalized rms vertical emittance	0.4 mm- mrad
Energy spread at 10 MeV, σ	15 keV (0.15%)
Pulse length (uniform distribution)	10 ps

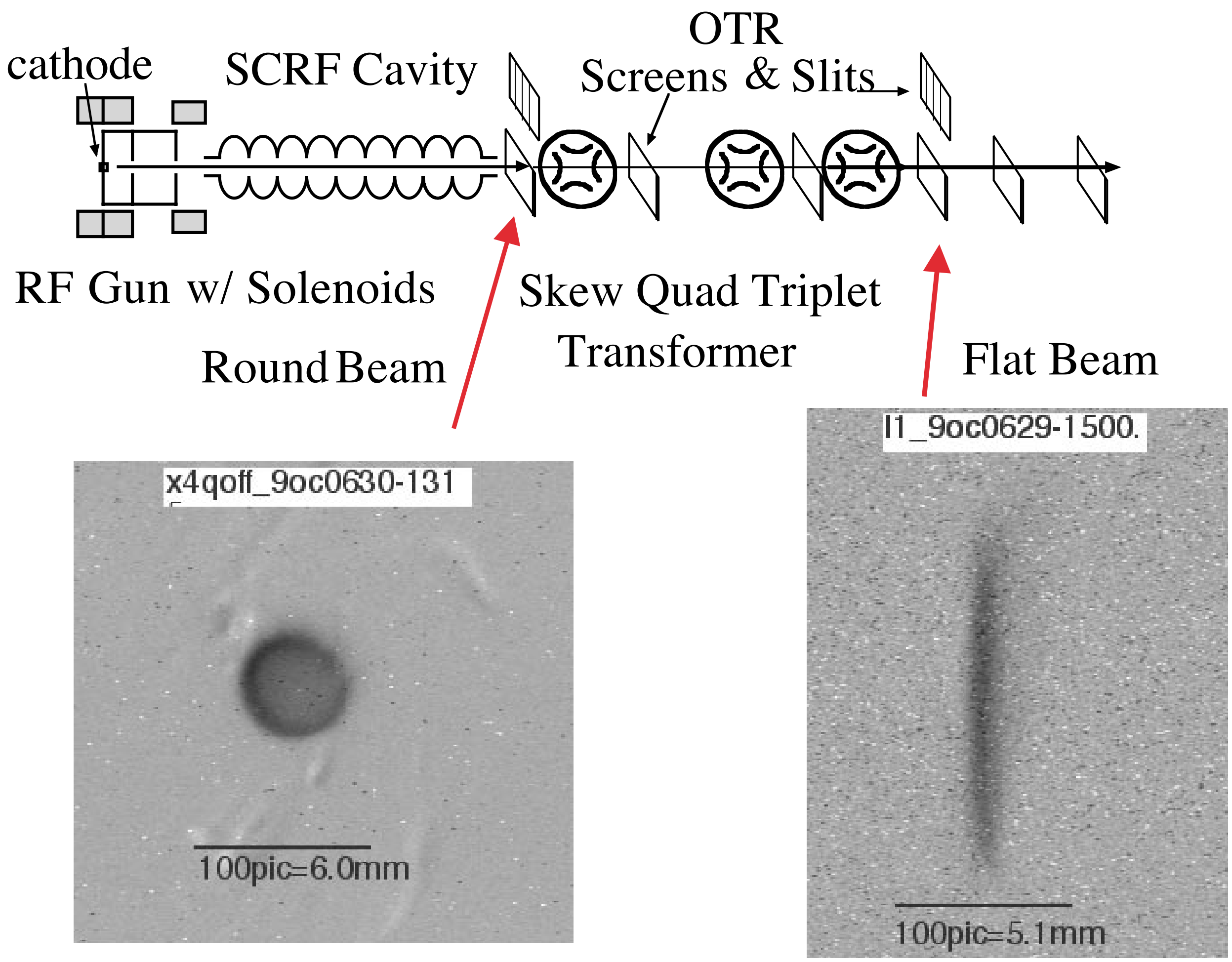
RF gun parameters:

RF frequency	1.3 GHz
Peak electric field on a cathode	~60 MV/ m
Repetition rate of injection pulses	10 kHz

Laser parameters:

Wavelength (Ti: sapphire 3rd harm.)	267 nm
Pulse energy	100 μJ
Pulse length (FWHM)	10 ps

Flat-Beam Transformation



Producing a flat-beam

Assumptions: Neglect thermal emittance at cathode, acceleration, focusing, or anything other than a constant solenoid field channel. The field strength is B_0. At the end of the solenoid channel, beam particles acquire angular momentum. The initial transverse coordinates (x_0, y_0) are mapped to:

$$\left. \begin{matrix} x \\ x' \\ y \\ y' \end{matrix} \right|_0 \longrightarrow \left. \begin{matrix} x \\ x' \\ y \\ y' \end{matrix} \right|_f = \begin{matrix} x_0 \\ -ky_0 \\ y_0 \\ kx_0 \end{matrix} \Bigg|$$

Here $k = 1/2\ B_0/(p_0/e)$, and p_0 is the initial momentum.

Producing a flat beam (2)

A quadrupole channel is used to convert this shearing beam into one with a high emittance ratio. The quadrupole channel need only present an identity transformation for x and a 90° phase advance for y:

$$\begin{vmatrix} x \\ x' \\ y \\ y' \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \beta \\ 0 & 0 & -1/\beta & 0 \end{vmatrix} * \begin{vmatrix} x_0 \\ -ky_0 \\ y_0 \\ kx_0 \end{vmatrix} = \begin{vmatrix} x_0 \\ -ky_0 \\ k\beta x_0 \\ -1/\beta\ y_0 \end{vmatrix}$$

$$\beta = 1/k, \text{ then } \longrightarrow \begin{vmatrix} x_0 \\ -ky_0 \\ x_0 \\ -ky_0 \end{vmatrix}$$

Flat beam at 45°. Use a skew quad channel to obtain an upright beam.

Achievable Emittance Ratio

With finite thermal emittance at the cathode, $\varepsilon_c = \sigma_c \, \sigma_c'$, and with an arbitrary value of the beam momentum, p_z, at the entrance to the quad channel

$$\boxed{\varepsilon_x / \varepsilon_y \sim 4k^2 \, \sigma_c^{\,2} / \sigma_c'^{\,2}}$$, where $k = 1/2 \, B_0/(p_z/e)$.

The matching condition for the quad channel then yields

$$\beta = 1/k \, \sigma_w^{\,2}/\sigma_c^{\,2}.$$

A0 Photoinjector is a good case study

Single pulse parameters have mostly been achieved at A0 Photoinjector facility already.

Emittance ratios of ~ 50:1 have been measured.

Measured emittances are ~ 2 times higher than required.

Bunch charges from 50pc to ~2nC can be produced in flat-beam mode.

Experimental Program at A0

We have begun a collaboration with Fermilab and A0 personnel that seeks to explore the limits of flat-beam production with this type of injector.

Our first visit (August 2001) acclimated us to the working environment and gave us a first hands-on control of the injector.

Our second visit (October 2001) concentrated on beam dynamics within the rf gun cavities, and emittance compensation effects, for a non-bucked-cathode injector.

Future visits will look towards characterizing the round-to-flat beam transformation process, available knobs, etc.

Results from Second Trip (October '01)

Nominal operating parameters:

Bunch charge ~0.5-1 nC.
Gun launch phase: 20° (flat), 40° (round).
Gun peak field ~35.7 MV/m.

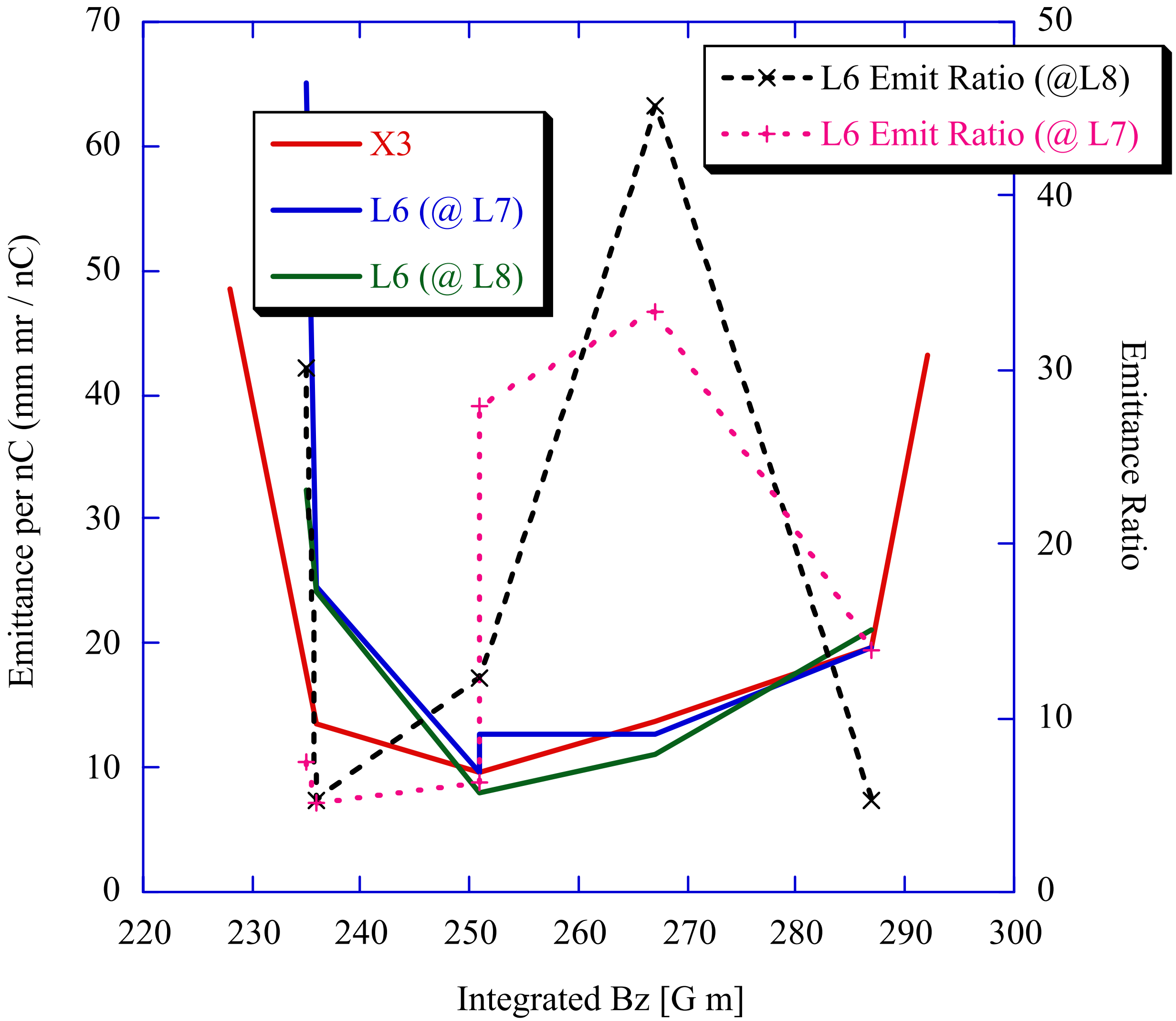
Laser spot size ~1-2 mm.
Laser pulse length FWHM ~5 ps.
Booster Cavity ~12 MV.

Studies

Day 1-2: Emittance compensation effects in gun and booster.
Day 3: Laser down.
Day 4: Bunch charge, laser spot size
Day 5: Rf phase and amplitude effects

The streak camera was not available on this excursion.

Integrated Bz-Field Influences both Emittance and Emittance Ratio



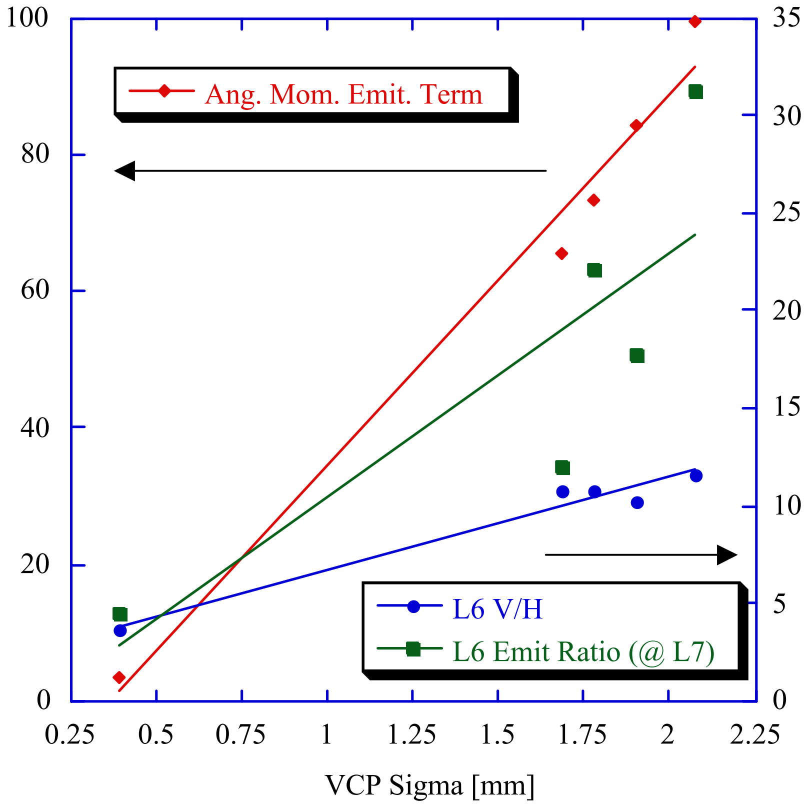
Suggested Optimization Factor-of-Merit:

Ratio / Emittance

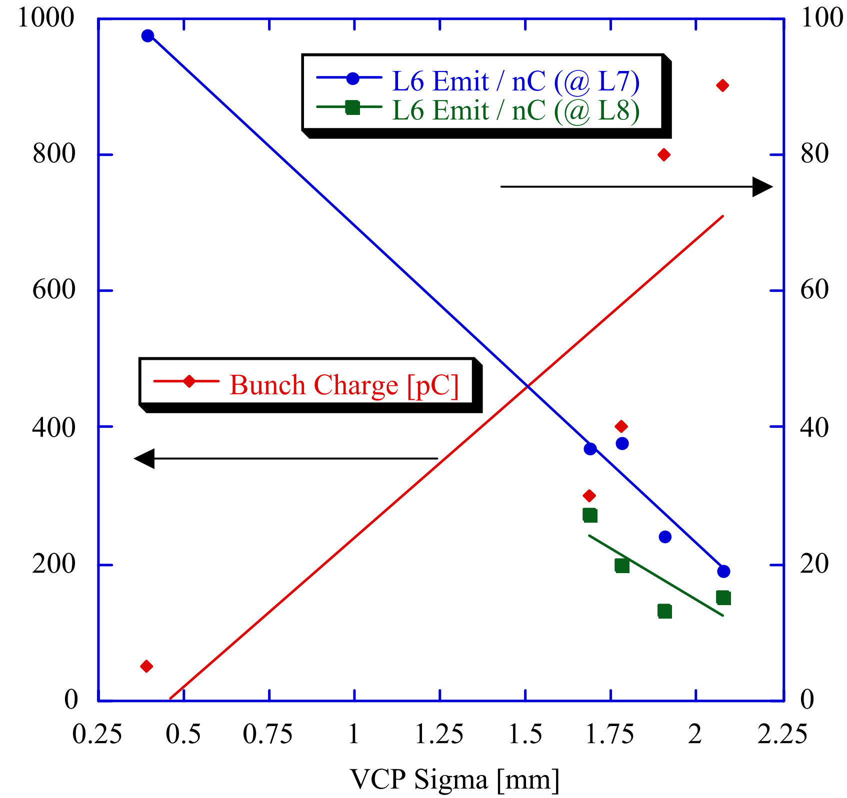
Spot size held fixed - Need to optimize for matching into quad channel.

Spot Size Determines Enclosed Flux and Emittance, Aspect Ratios

Emittance and Aspect Ratios



Bunch charge and Emittance



Solenoid and quadrupole tunes held fixed.

Issues in the Experimental Program

1. Cathode QE decreases by factor of 5-10 in flat-beam mode, over a period of 10's of minutes, then recovers once the field is bucked out again.
2. Optimum gun rf launch phase changes from 40° (round) to 20° (flat). Why?
3. The beam emittance increases by ~2 in flat beam mode.
4. There is considerable aberration in the beam profile under typical conditions.
5. Laser system is habitually unstable. Difficult to obtain consistent sets of scans for parametric studies.
6. Slit measurements are resolution-limited at L7, and noise-limited at L8.

Current Work

•Understanding beam dynamics in the gun.

No agreement yet between the various models.

•Developing end-to-end simulation models.

-Collaboration with Fermilab personnel.

•Benchmarking these simulations against measurements.

And then . . .

•Parametric studies of flat beam production.

•Evaluation of current diagnostics for measurements of high aspect-ratio beams.

Future Experimental Work

Future trips must look in greater detail at the round-to-flat transformation optics and how they impact gun design and operating parameters.

1. Studies of the round-to-flat beam transformation – linear optics.
2. Studies of the round-to-flat beam transformation – nonlinear optics and space charge effects. Curvature of solenoid field at cathode, use of sextupoles in the beamline, . . . ?
3. Diagnostics and instrumentation for higher aspect ratio beam profiling and emittance measurement.
4. Studies of the solenoid-field-dependent loss of quantum efficiency, and necessary re-tuning of the gun launch phase.
5. Studies of other photocathodes and photoinjectors?

After that . . .

We need to keep in mind that the desired femtosecond injector design will be similar to A0's, but will incorporate new features and optimized parameters aimed at flat beams.

- Higher peak gradients in the rf gun and kHz rep rates require a new gun design.
- Solenoid magnets may be placed in a very different configuration, since a bucking arrangement is no longer necessary.
- The pulse compressor will be placed after the round-to-flat transformation lattice, thus changing the placement of the quads from what is present at A0.
- We need to be cognizant of alternative injection systems (e.g. plane-wave transformers), and of photocathode R&D.